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The Vulnerability of Electric Equipment to
Carbon Fibers of Mixed Lengths - An Analysis

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THE VULNERABILITY OF ELECTRIC EQUIPMENT TO CARBON FIBERS OF MIXED LENGTHS -- AN ANALYSIS

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SUMMARY

The vulnerability of electric equipment to airborne graphite fibers of mixed lengths has been analyzed. The method uses data from tests with fibers of uniform lengths. Sample results are presented for a stereo amplifier together with a statistical analysis of the failure distribution for three failure criteria.

INTRODUCTION

Graphite or carbon fibers produced for structural applications may cause electrical problems because they are electrically conductive. During the manufacture of composites, or if the resin is burnt out of the composite, these fibers can be released into the atmosphere. Because they are light and have only 7 μm original diameter, their fall velocities in air are only 25mm/s. With such low fall velocities, the natural turbulence in the atmosphere can keep the fibers airborne for many hours.

The graphite fibers have resistances of about 500 k Ω /m and will carry currents of up to 15 mA without burning. Many electrical circuits will malfunction if a fiber of such resistance is deposited across contacts without receiving sufficient fault current to burn away the fiber.

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For an electrical or electronic instrument operating in an atmosphere containing graphite fibers, the rate of ingesting fibers is proportional to the airborne fiber concentration, and the total risk of failure is normally proportional to the time integral of the concentration or the exposure. The exposure is given the symbol E and has units of fiber-sec/ meter³ ($f \cdot s/m^3$).

As part of a program to determine the risk of using graphite fibers in aircraft structures (ref.1), many electrical instruments have been tested to establish their vulnerability to graphite fibers that may be released from aircraft crash fires. These tests have been performed in specially designed test chambers where fibers of essentially uniform lengths were dispersed in the atmosphere at controlled concentrations. The results of these tests have provided values for the mean exposure-to-failure (\bar{E}) as a function of fiber length for these instruments.

Normally, the fibers released when pieces of graphite-epoxy composite are burnt have non-uniform lengths, typically an exponential distribution with a mean length near 2mm. This report presents the methods developed to calculate the mean exposure-to-failure under such a spectrum of fiber lengths from the vulnerability data obtained with uniform-length fibers in the chambers. Such methods were developed and presented here for cases where the complete fiber length spectrum is known and for cases where only the distribution of the fibers longer than 1mm is known, but where the effect of the smaller fibers is also included by extrapolation.

A stereo amplifier was exposed to fire-released fibers and to chopped fibers of uniform lengths to compare its vulnerability to both environments (ref.2). Because two channels were operating, three failure criteria were inherent: failure of the first of the two channels, failure of both channels, or failure of one specific channel. The methods for predicting the mean exposure-to-failure under each of these criteria were developed and are reported.

LIST OF SYMBOLS

E	fiber exposure, $f \cdot s/m^3$
E_f	exposure at failure, $f \cdot s/m^3$
\bar{E}_a	mean exposure to failure of amplifier, $f \cdot s/m^3$
\bar{E}_c	mean exposure to failure of channel, $f \cdot s/m^3$
\bar{E}_ℓ	mean exposure to failure at length ℓ , $f \cdot s/m^3$
\bar{E}_1	exposure constant
E^*	mean exposure to failure in spectrum environment, $f \cdot s/m^3$
E_a^*	E^* for an amplifier, $f \cdot s/m^3$
E_c^*	E^* for one channel, $f \cdot s/m^3$
ℓ	fiber length, m
ℓ_e	equivalent fiber length, m
ℓ^*	mean fiber length of exponential spectrum, m
n	vulnerability exponent
$P[\]$	probability distribution
$p(\chi_1)$	probability density function
X	specific variable value
χ	normalized exposure, E/\bar{E}
$\alpha(\ell)$	fiber length distribution function
$\beta(\ell)$	fiber length distribution function

ANALYSIS

Spectrum Vulnerability Based On Uniform Length Data

The analysis of the vulnerability of a piece of electric equipment to a spectrum of lengths of fibers is simple if no interactions between the individual fibers need to be considered. For many equipment types the test results showed that the probability that the exposure to failure E_f is equal to or less than E had an exponential distribution.

$$P[E_f \leq E] = 1 - e^{-E/\bar{E}_\ell}$$

Only a random process in which failure results from only one of many fibers falling onto a circuit would provide this exponential failure distribution. Because there is only one fiber involved in the failure all fibers in a spectrum can be assumed to act independently.

The following derivation produces an expression for the mean exposure to failure in an environment of fibers of non-uniform lengths based on data from tests with fibers of uniform length.

Because the probability of survival from a small exposure ΔE of fibers of length ℓ is

$$P_s = e^{-\Delta E/\bar{E}_\ell}$$

the probability of survival after a series of such small exposures ΔE_i is

$$P_s = e^{-\Delta E_1/\bar{E}_\ell} e^{-\Delta E_2/\bar{E}_\ell} \dots$$

$$= e^{-\sum \Delta E_i/\bar{E}_\ell}$$

Now, because fibers of different lengths are considered to act independently, each small exposure ΔE_i can be considered to result from fibers of length ℓ_i , so that the probability of survival is

$$P_s = e^{-\sum \Delta E_i / \bar{E}_{\ell_i}}$$

if the length distribution of the fiber spectrum is defined by a distribution function $\alpha(\ell)$, such that

$$E_{\ell} = \alpha(\ell) E$$

then with an integration replacing the summation, the probability of survival is

$$P_s = e^{-\int_0^{\infty} \frac{\alpha(\ell) E}{\bar{E}_{\ell}} d\ell}$$

This can be simplified by defining a mean exposure to failure for that fiber spectrum E^* such that

$$E^* = 1 / \int_0^{\infty} \frac{\alpha(\ell)}{\bar{E}_{\ell}} d\ell$$

The probability of failure still has an exponential distribution which is then

$$P[E_f \leq E] = 1 - e^{-E/E^*}$$

Spectrum Vulnerability For An Exponential Fiber Spectrum

For the specific case of fire-released fibers shown in Figure 1, the distribution of fiber lengths is almost exponential with a mean length of ℓ^* , such that the distribution function is

$$\alpha(\ell) = \frac{1}{\ell^*} e^{-\ell/\ell^*}$$

Often the vulnerability test data can be represented by an inverse power law. This applies to the data for the sample stereo amplifier shown in Figure 2, where the solid line represents the failure criterion for the first failure of the two channels (\bar{E}_a), and the dashed line represents the failure criterion for the individual channels (\bar{E}_c). The power law relation for these failure curves is

$$\bar{E}_\ell = \bar{E}_1 / \ell^n$$

where \bar{E}_1 is a constant equal to the exposure to failure at 1mm fiber length, and the exponent is $n=2.61$ for this amplifier.

For the exponential fiber length spectrum and for this inverse power law vulnerability the mean exposure to failure is

$$\begin{aligned} 1/E^* &= \int_0^\infty \frac{\ell^n e^{-\ell/\ell^*}}{\ell^* \bar{E}_1} d\ell \\ &= \frac{\sqrt{(n+1)} \ell^{*n}}{\bar{E}_1} \end{aligned}$$

or for integer values of the exponent n

$$1/E^* = \frac{n! \ell^{*n}}{\bar{E}_1}$$

An equivalent fiber length ℓ_e , that yields a vulnerability equal to the spectrum vulnerability E^* for a spectrum of lengths,

may be defined as

$$1/\bar{E}_{\ell e} = \frac{\ell_e^n}{\bar{E}_1} = \frac{1}{E^*} = \frac{\sqrt{(n+1)} \ell^{*n}}{\bar{E}_1}$$

The ratio of the equivalent fiber length to the mean fiber length for the spectrum is then

$$\ell_e/\ell^* = \left(\sqrt{(n+1)} \right)^{1/n}$$

Figure 3 shows this relation in the range from $n=1$ to 4, which covers the range of exponents of all equipment tested. This result, which applies specifically to an exponential fiber length distribution, shows that an equivalent fiber length is of the order of 50% greater than the mean fiber length of the spectrum.

Incompletely Defined Fiber Length Spectra

Because the fibers shorter than 1mm were difficult to count, and were not expected to contribute to the failures in equipment tested, the fiber count and exposure measurement in the outdoor tests were based on only those fibers longer than 1mm.

If the length distribution $\beta(\ell)$ of fibers longer than 1mm is defined such that

$$\int_1^{\infty} \beta(\ell) d\ell = 1$$

the vulnerability under the spectrum is

$$1/E^* = \int_1^{\infty} \frac{\beta(\ell)}{\bar{E}_{\ell}} d\ell$$

To include the contribution of the short fibers in the damage assuming that the same physical laws apply, the distribution $\beta(\ell)$ can be extrapolated into the region $0 < \ell < 1$. A more damaging estimate of the vulnerability is obtained by changing the integration limits to

$$1/E^* = \int_0^{\infty} \frac{\beta(\ell)}{\bar{E}_\ell} d\ell$$

If the distribution of the fibers longer than l_{mm} is exponential, such that

$$\beta(\ell) = \frac{1}{\bar{\ell}-1} e^{-(\ell-1)/(\bar{\ell}-1)}$$

in which $\bar{\ell}$ is the mean length of the fibers longer than l_{mm} , then with $\ell^* = \bar{\ell}-1$

$$\beta(\ell) = \frac{1}{\ell^*} e^{\ell/\ell^*} e^{-\ell/\ell^*}$$

If the functional form of this distribution is also valid in the range $0 < \ell < 1$, then

$$1/E^* = e^{\ell/\ell^*} \int_0^{\infty} \frac{\ell^n e^{-\ell/\ell^*}}{\ell^* \bar{E}_1} d\ell$$

This expression differs from the similar expression in the previous section by the factor e^{ℓ/ℓ^*} . This expression was used to derive the mean exposure to failure expected for the amplifiers in outdoor tests.

For fiber length spectra that do not have the simple exponential functional form, the spectrum vulnerability is most easily calculated by a summation process. An example for a full fire-released fiber spectrum is given in the Appendix.

Statistical Analysis of Failure Criteria

The stereo amplifier tested in this program had two independent channels. Most tests were conducted with both channels active, until the first channel failed. This failure criterion produced a mean exposure to failure different from the tests in which the exposure to failure of each channel was recorded independently, or in which the failure of the second channel was taken as the failure criterion. The statistical differences between these criteria have been analyzed and are presented in this section.

If each channel has a mean exposure to failure \bar{E}_c , the mean exposure to failure of the amplifier with two channels \bar{E}_a is desired for the following failure criteria;

- (a) failure of the first of the two channels ; and
- (b) failure of both channels.

If the failure distribution for each individual channel is exponential and a non-dimensional exposure parameter is defined as

$$\chi = E/\bar{E}_c$$

then the probability density functions for the two channels can be written as

$$p(\chi_1) = e^{-\chi_1}$$

$$p(\chi_2) = e^{-\chi_2}$$

Figure 4 is a two-dimensional representation of the non-dimensional parameters χ_1 and χ_2 . This failure plane is subdivided into four regions A, B, C, and D. Region A represents a failure condition where both channels have exposures to failure larger than a test value X. Region B represents failure conditions in which both channels have exposures to failure smaller than the test value X. Regions C and D represent conditions in which one channel has an exposure to failure less than X, and the other channel has an exposure to failure larger than X.

For conditions described by the region A the probability that $\chi_1 \geq X$ and that $\chi_2 \geq X$ is

$$\begin{aligned} P[\chi_1 \geq X \cap \chi_2 \geq X] &= \int_X^\infty e^{-\chi_2} \int_X^\infty e^{-\chi_1} d\chi_1 d\chi_2 \\ &= e^{-2X} \end{aligned}$$

For region B

$$\begin{aligned} P[\chi_1 \leq X \cap \chi_2 \leq X] &= \int_0^X e^{-\chi_2} \int_0^X e^{-\chi_1} d\chi_1 d\chi_2 \\ &= (1 - e^{-X})^2 \end{aligned}$$

For region C

$$P[\chi_1 \leq X \cap \chi_2 \geq X] = \int_X^\infty e^{-\chi_2} \int_0^X e^{-\chi_1} d\chi_1 d\chi_2$$

For region D

$$\begin{aligned} P[\chi_1 \geq X \cap \chi_2 \leq X] &= \int_0^X e^{-\chi_2} \int_X^\infty e^{-\chi_1} d\chi_1 d\chi_2 \\ &= e^{-X} (1 - e^{-X}) \end{aligned}$$

These four conditions cover all possibilities and hence the four probability expressions sum to unity.

According to the failure criterion (a) the failure occurs when the first of two channels fails. The probability of having at least one failure is the complement of the probability of having

no failures, or the complement of region A. This probability has a distribution of

$$P[\chi_1 \cup \chi_2 \leq x] = 1 - e^{-2x}$$

for which the probability density function is

$$p(\chi_1 \cup \chi_2 \leq x) = 2 e^{-2x}$$

and the expected value $\bar{\chi}$ is

$$\bar{\chi} = \int_0^{\infty} 2x e^{-2x} dx = 1/2$$

This shows that under the failure criterion (a) the mean exposure to failure for the first of two channels is one half of the mean exposure to failure for the individual channels, and that the distribution of failure is still exponential.

For the failure criterion (b) the probability distribution is that described by region B, namely, the probability that both channels have failed at less than the value x . This probability is

$$P[\chi_1 \leq x \cap \chi_2 \leq x] = (1 - e^{-x})^2$$

for which the probability density function is

$$p(\chi_1 \leq x \cap \chi_2 \leq x) = 2e^{-x} - 2e^{-2x}$$

for which the expected value is

$$\bar{\chi} = \int_0^{\infty} (2xe^{-x} - 2xe^{-2x}) dx = 3/2$$

With this failure criterion, the failure of the second of the two channels, the mean exposure to failure is then one and one half times the mean exposure to failure for the individual channels.

Amplifier Vulnerability Data Analysis

In figure 2, the triangular symbols represent the results of tests carried out at the Ballistics Research Laboratory [3]. Each test point represents the mean of four individual tests carried out with Thornel T-300 fibers. The round symbol is a data point from a series of tests carried out by the Bionetics Corporation on the same model amplifier with 1mm T-300 fibers [4]. In both test series the failure of the first channel was the failure criterion for the failure of the amplifier. The solid line in figure 2 is an inverse power law fit to these data, and represents the mean exposure to failure of the amplifier to clean, chopped T-300 fibers. An expression for this curve is

$$\bar{E}_a = \frac{5.9 \cdot 10^7}{\ell^{2.61}}$$

where ℓ is the fiber length in mm. The mean exposure to failure for each individual channel is represented by the dashed line in figure 2 and has a similar power law fit with a constant of $1.18 \cdot 10^8$.

Fiber Length Spectrum Analysis

In tests in the Dahlgren Shock Tube Facility [2] strips of graphite composite materials were burned in a rotating screen barrel. Any fibers released were carried with the sooty fire plume along the shock tube to the fire table, where six stereo amplifiers were exposed to these fibers. The fiber concentrations were sampled by several techniques. Table 1 shows a fiber length analysis from one adhesive tape sampler. The mean length of the 218 fibers in the sample was 1.76mm. Figure 1 shows a histogram representation of the experimentally determined fiber length distribution, together with the exponential distribution fitted to those data. That distribution is

$$\alpha(\ell) = 1/1.76 \ e^{-\ell/1.76}$$

Table 1
Fiber Length Analysis Results from Dahlgren Tests

Length Interval, mm	Number in Interval	% in Interval
<1	96	44
1-2	52	24
2-3	30	13
3-4	21	10
4-5	12	5
5-7	3	2
>7	4	2

Calculation of Spectrum Vulnerability

Because the complete spectrum is defined the mean exposure to failure is obtained from

$$1/E^* = \sqrt{(n+1)} \ell^{*n} / \bar{E}_1$$

The Gamma-function of $n+1$ was obtained from standard mathematical tables $\sqrt{(3.61)} = 3.75$. The mean exposure to failure for the first of two channels was therefore determined to be $3.6 \cdot 10^6 \text{ f} \cdot \text{s/m}^3$.

The equivalent fiber length for this amplifier in this fiber spectrum was 2.92mm. This shows that, although only 19% of the fibers in the spectrum are 3 mm or longer the spectrum acts as if all fibers were 3mm long.

CONCLUDING REMARKS

An analysis has been presented for the calculation of the vulnerability of electric instruments to graphite fibers of mixed lengths based on test data with fibers of uniform lengths. Also the logic has been developed to calculate the mean exposure to failure of the first of two instruments, or the last of two instruments from the data for a single instrument. The analyses have

been applied to predict the mean exposure to failure of a stereo amplifier exposed to fibers released from graphite composites burned in jet fuel. The results of this analysis, when combined with the exposure probability, can be used to determine the probability of equipment failure.

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3. Stumpf, Charles R.; and Weaver, Calvin E.: Measured Carbon Fiber Exposures to Malfunction for Civilian Electronic Items. ARBRL-MR-02943, U. S. Army Ballistics Research Laboratory, 1980.
4. Experimental and Analytical Studies for the NASA Carbon Fiber Risk Assessment. (The Bionetics Corporation, NASA Contract NAS1-15238). NASA CR-159214, 1980.

APPENDIX

Because the lengths of identifiable fibers released from fires range from less than 10 μm to more than 10mm, no single microscope technique was suitable to count and measure all fibers. The fiber count of "long fibers" in Table 1 was produced under a low-power microscope. The count of the fibers shorter than 1mm is therefore considered unreliable.

A sample of fibers from the same fire was analyzed under an electron microscope. The fiber length distribution thus obtained is given in Table 2. It shows some counts for fibers longer than 1mm, but here those counts must be considered unreliable because the length measurements had to be made over a very large number of fields of view in the microscope. To obtain the best estimate of the actual distribution of fiber lengths released from the fire a joint spectrum was synthesized from the two partial distributions by matching them in the vicinity of 1mm fiber length. The spectrum shown in Table 3 consists of all the fibers shown in Table 1 above 1mm, and 2.13 times the number of short fibers from Table 2 below 1mm.

Because the number of fibers below 1mm in length is very much larger than would be assumed in an exponential spectrum an analysis was required to show that the contribution to the damage from these short fibers could really be ignored, besides not being counted.

Using the methods developed for incompletely defined spectra, a distribution function $\beta(\ell)$ was developed based on the fibers longer than 1mm, and was extended for the short fibers to assess their contribution to the damage. Table 3 also shows the values for this distribution function. Using a summation process rather than an integral, the mean exposure to failure resulting from the long fibers is

$$1/E^* = \sum_{\ell=1}^{\infty} \frac{\beta(\ell)}{\bar{E}_{\ell}}$$

and the mean exposure to failure resulting from all the fibers but still based only on the count of the long fibers is

$$1/E^* = \sum_{0}^{\infty} \frac{\beta(\ell)}{\bar{E}_{\ell}}$$

Using the uniform fiber length data for the stereo amplifier

$$\bar{E}_{\ell} = 5.9 * 10^7 / \ell^{2.61}$$

the following values were obtained. The mean exposure to failure based only on the long fibers is $2.47 * 10^6$ f.s/m³ and the mean exposure to failure for all fibers is $2.38 * 10^6$ f.s/m³. Thus failure would be expected to occur 4% earlier than if the calculation was based on the long fibers only.

Within the overall accuracy required for the risks from graphite fibers the foregoing results show that the fibers shorter than 1mm can be ignored.

Table 1
Long Fiber Distribution

Length Interval, mm	Number in Interval
<1	96
1-2	52
2-3	30
3-4	21
4-5	12
5-7	3
>7	4

Table 2
Short Fiber Distribution

Length Interval, μm	Number in Interval
10- 18	3
18- 32	12
32- 56	66
56- 100	87
100- 178	117
178- 316	154
316- 562	80
562-1000	39
1000-1780	19
1780-3160	7
3160-5620	4
>5620	1

Table 3
Synthesized Full Distribution

Length Interval, μm	Number in Interval	Distribution function, $\beta(\ell)$
10- 18 μm	6	0.049
18- 32	26	0.213
32- 56	141	1.156
56- 100	186	1.525
100- 178	250	2.049
178- 316	329	2.697
316- 562	171	1.402
562-1000	83	0.680
1-2 mm	52	0.426
2-3	30	0.246
3-4	21	0.172
4-5	12	0.098
5-7	3	0.025
>7	4	0.033

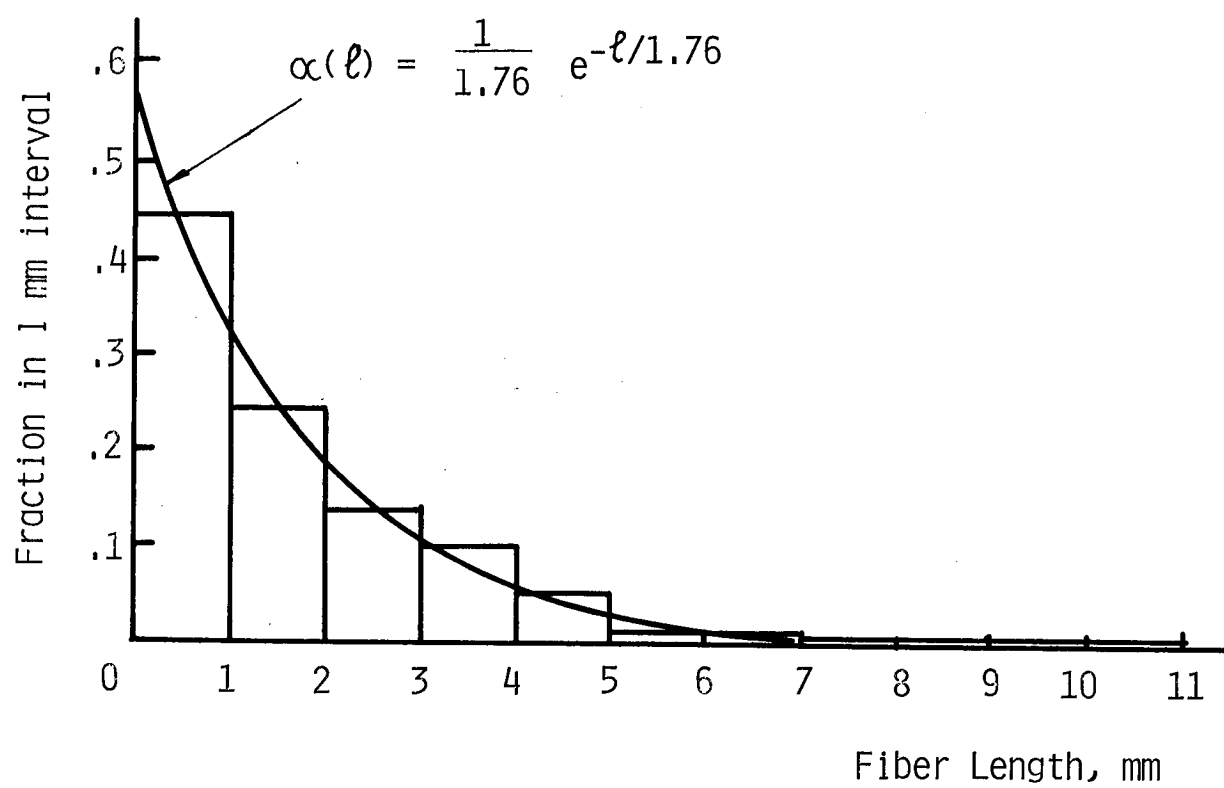


Figure 1. Experimentally Determined Fiber Length Distribution

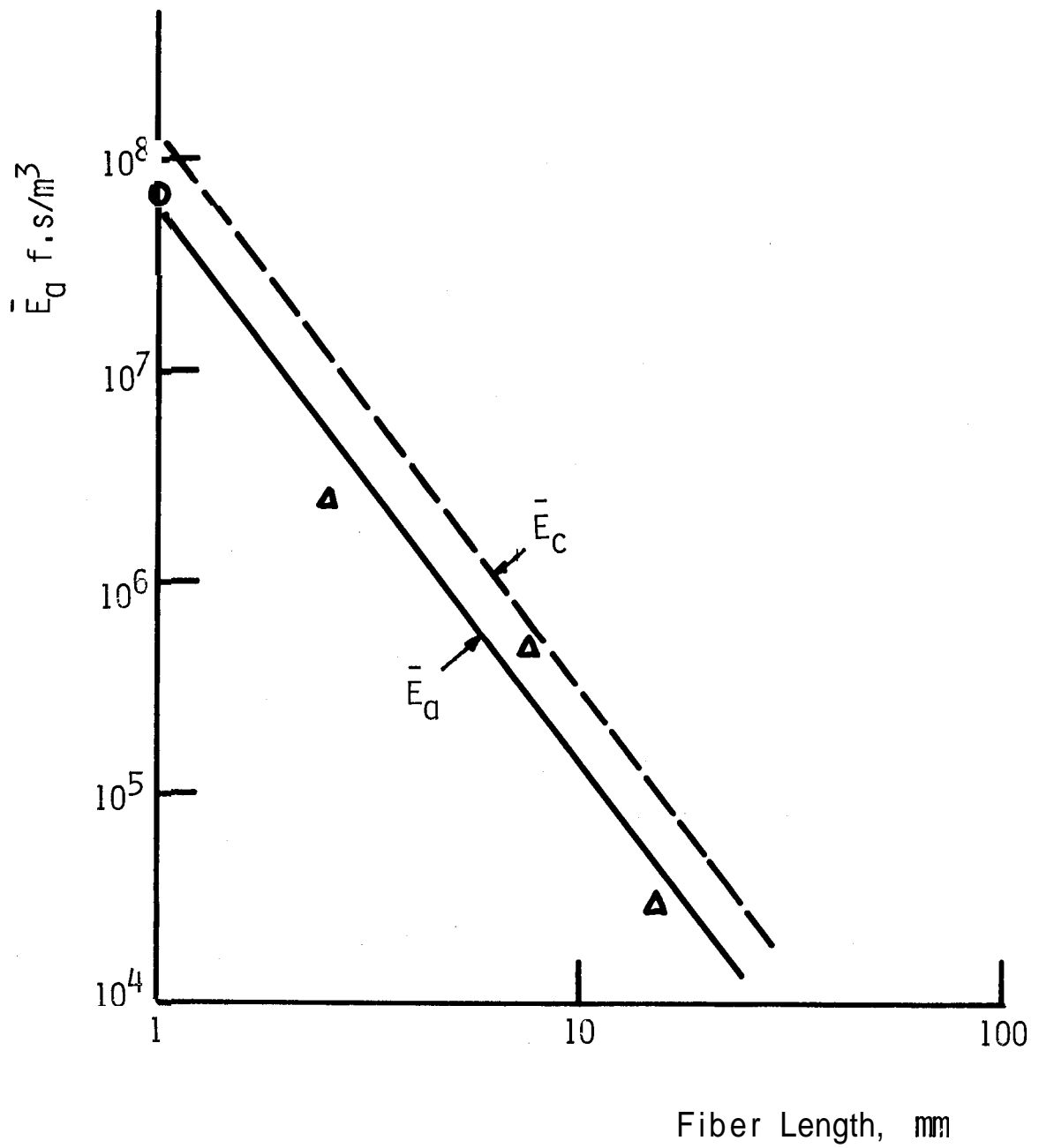


Figure 2, Failure Data for Stereo Amplifier

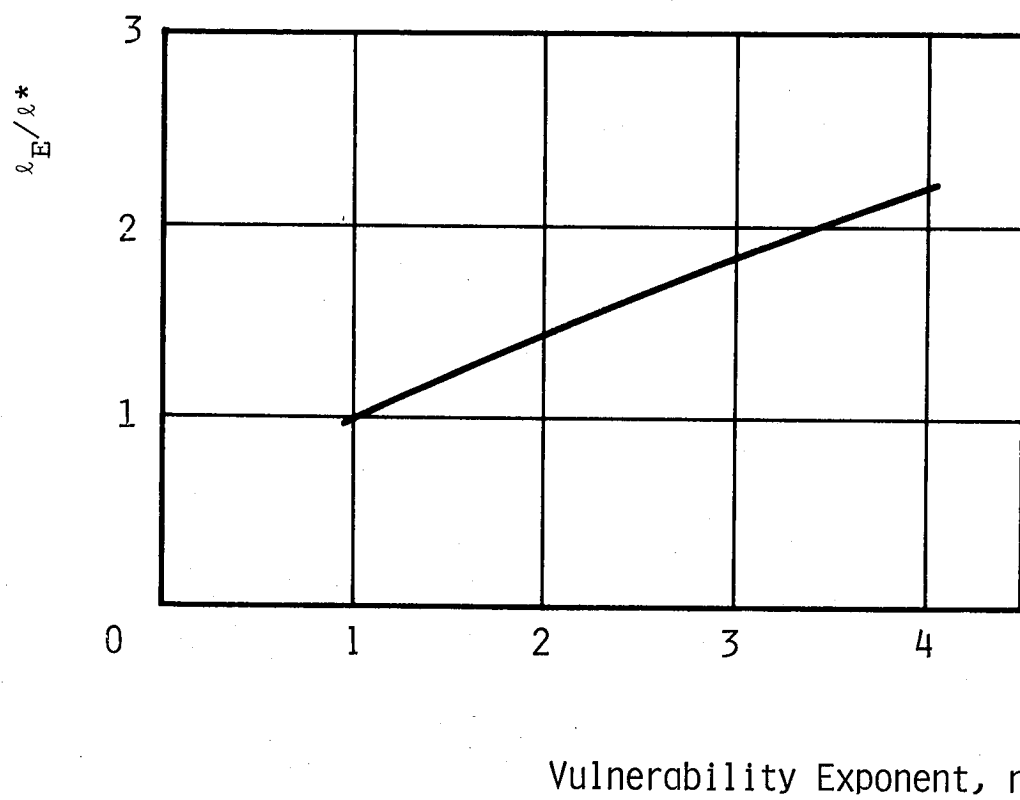


Figure 3. Equivalent Fiber Length as a function of Vulnerability Exponent

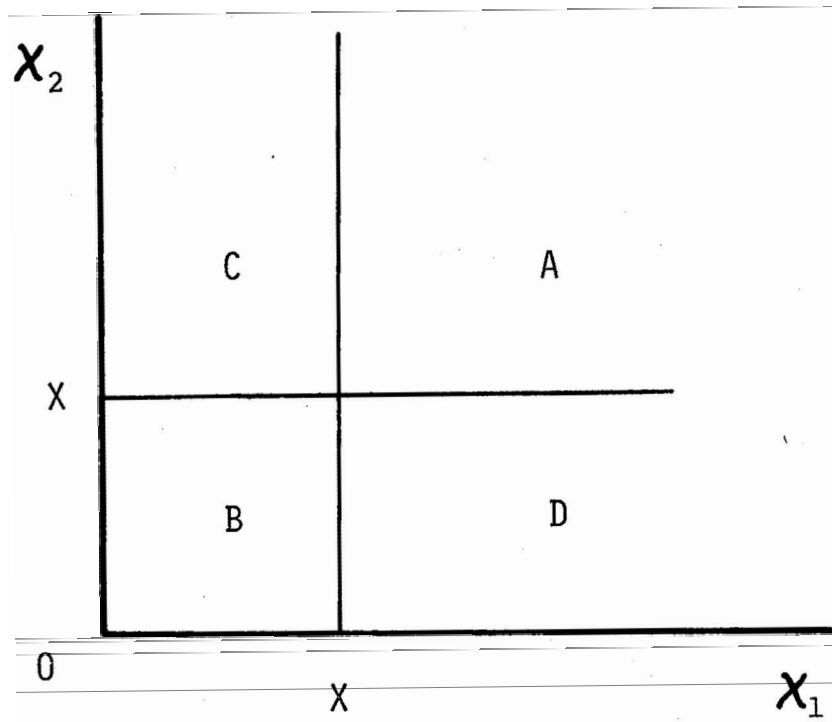


Figure 4. Failure Plane Subdivision

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